Application of High Resolution Seismic Imaging Methods for Fracture Quantification

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Abstract

Over the past several years as part of the Department of Energy's FETC fractured gas program, we have been developing and applying the use of high resolution seismic methods to define and map the permeable pathways in naturally fractured gas reservoirs. This work involves an iterative approach between theoretical, laboratory, modeling, controlled field work and large scale field work to develop and validate the appropriate seismic methods for not only determining the existence of fractures but for defining the fractures that control transport. The work has been focused on single and multiple component borehole sources in crosswell and single well configurations to record multicomponent data at frequencies from fifty to several kilohertz. Work to date shows that while surface methods provide broad characterization of fractures, borehole methods are necessary for providing the resolution necessary for inferring actual transport properties in fractured media. Although direct imaging of fractures is possible, other effects such as anisotropy, scattering and guided waves are also diagnostic of fracture characteristics in both velocity and amplitude analysis.

Theory

During the past several years there has been considerable effort in developing seismic imaging methods for fracture characterization. Most of these methods have focused on surface techniques using P-wave (for a comprehensive state of the art review see Tsvankin and Lynn, 1999) and occasionally S-wave methods (Schoenberg and Sayers, 1995). The result of many of these applications has been mapping of P-wave anisotropy, presumably due to fractures. However, due to limited bandwidth and resolution few if any of the surface based techniques have been able to derive the resolution to map the fracture(s) actually responsible for transport. Recent theoretical work, however, at Lawrence Berkeley National Laboratory (LBNL)(Kalen 1998, Nihei et al,1999, Nakagawa et al 1999) suggest that using higher resolution methods it may be possible to image fracture properties beyond anisotropic effects. These studies suggest that crosswell and single well data acquisition configurations would be appropriate for gathering the data required to image fracture properties.

One theoretical model for a fracture replaces the fracture by a zero thickness compliant layer. The compliance (inverse of stiffness) of the layer is related to the porosity of the fracture as well as what fills the porosity. The key characteristics of the model is that phase and amplitude change can be related to measurable fracture stiffness even though a layer of zero thickness is assumed. Results for a plane wave normally incident upon a fracture are shown in Figure 1. As fracture stiffness (k) decreases, frequency dependent decreases in amplitude and velocity are predicted. The theoretical model also predicts that energy can be trapped by a fracture, propagating as a generalized Rayleigh wave. Figure 2 is numerical simulation showing a snapshot of the wavefields generated by vertical and horizontal point sources. The trapped waves are designated by RIW. Snapshots of the wavefield with no fracture present are shown for comparison. In order to characterize fractured reservoirs, effects of multiple fractures must be modeled. Figure 3 is a snapshot of the wavefield for an explosion source in a medium containing equally spaced fractures of infinite extent for high fracture stiffness (top) and low fracture stiffness (bottom). Figure 4 is a snapshot of the wavefield for a case of a plane wave incident on a single layer containing fractures of finite length and irregular spacing. Reflected and transmitted waves, as well as diffracted waves are observed.

Field Scale Application

In order to test these theories LBNL has performed several different scale experiments under controlled conditions at several different fractured sites. The main site was the Conoco borehole test facility near Newkirk Oklahoma. The site (Queen et al., 1992), contains six deep and five shallow wells used for geophysical and hydrological tests. The site occupied for the subject experiments consists of the five shallow groundwater wells (GW) in a "5-spot" pattern with the outside wells approximately 50 meters from the center well (Figure 5). The shallow wells penetrate a fractured shale and limestone sequence of the Lower Permian Chase Group (Queen and Rizer, 1990). Considering the pump test data, (Sheely, 1991) the fracture orientations/character of fractures mapped in the near by out-crops, and the seismic anisotropy together, we felt that there was strong evidence for a fracture controlled transport system. Therefore, both crosswell and single well surveys were carried out in the wells before, during, and after air was injected in well GW-5 (to enhance seismic visibility over a fully saturated fracture). Frequencies from 1,000 to 10,000 Hz were used.

Applying the theories above, one would expect a significant effect on the crosswell data if air had migrated between any of the crosswell pairs (the stiffness of the fracture had significantly changed due to air displacing water, thus making the fracture less stiff and more of a filter and reflector to a seismic wave). The crosswell results were quantified by calculating a summed spectral amplitude over a specified frequency band (4000 to 6000 Hz) in 0.08 millisecond time steps along each trace at each depth. This band was chosen because this is the band in which we had maximum power. The result is a time-amplitude plot for each trace. Figure 5 shows the crosswell spectral amplitude data between well pairs GW-3/GW-1 and GW-3/GW-4 before and after air injection. For GW-3/GW-1 path almost for all traces show a sharp decrease in the amplitude of the first arrival. However, the GW-3 to GW-4 crosswell first arrival signals look virtually identical before and after the air injection. The only significant difference between the before and after data from GW-3 to GW-4, is the increase in amplitude of a secondary arrival at 17 milliseconds. The large decrease in seismic energy produced when introducing air into the fracture is easily seen in these plots. The crosswell pairs GW-3 to GW-5 and GW-3 to GW-2 are similar to GW-3 to GW-1. We assume this is due to effects of air being injected at GW-5, and the water level in GW-2 being drawn down.

The single well data in GW-3 also showed a large change in reflectivity before and after the air injection, indicating that the fracture was acting as a reflector, i.e. the reflectivity increased when air was injected into the fracture, Figure 6. This was consistent with the transmission decreasing as shown in the crosswell data (Figure 1).

From the crosswell data it was determined that there was a fracture somewhere between GW-3 and GW-1, from the single well data it was determined that the distance to the fracture was 17 meters. A slant well was drilled on the seismic data and a fracture was encountered at the predicted place. To determine if that indeed was the permeable fracture, GW-5 was injected with air to see if the air was observed directly in the fracture encountered in the slat well. Air was observed, therefore giving proof that this was "the" fracture. It should be added that no other fractures were encountered in the slant well. In a related follow-up experiment a seismic source (same piezoelectric source used in the crosswell and single well) was placed in GW-5 to "shoot down the fracture" to confirm the fracture location and to explore such diagnostics as guided wave and other seismic diagnostics. Shown in Figure 7 is the result of this guided wave experiment. This figure shows that the wave that travels along the fracture changes amplitude as the air content changes, again confirming the fracture stiffness theory.

Another approach to interpreting the data was to a apply a mixing theory to the results. That is treat the fracture as a air-water medium (Kalen 1999). Shown in Figure 8 are the predicted seismograms, moduli and phases for different air concentrations ranging from 0 to 50 percent air if one assumes this model. This implies that the velocity drops to very low values in the fracture thus making the wavelength small at the high frequencies used, on the order of the fracture dimensions of a few centimeters. Also, shown in Figure 8 are estimates of the fracture aperture and content using this approach. These values agree very well with the observed values in core across the fracture.

Discussion and Conclusions

Before this work began we were uncertain that seismic methods could map fracturing, or heterogeneity at a fine enough scale to provide useful information for fluid transport models. Although we by no means claim to have solved the problem, we feel that we have taken a step towards providing an approach to characterizing fractured heterogeneous environments. The high frequency approach described in this paper is the end result of starting out with conventional low resolution methods (VSP and surface reflection, which yielded little useful information) and ending up with a combination of seismic methods (crosswell and single well) to map conductive features. We feel that there are several significant results from this work.

1. We have demonstrated that single well reflection surveys can provide useful information on vertical features a significant distance from the well. Single well surveys hold great promise in characterizing fine scale reservoir heterogeneity, but due to operational issues (tube waves, horizontal velocity gradients, lack of commercial systems) the method has not been extensively used.

2. This work has shown that relatively small fractures can account for significant fluid flow. Methods such as VSP and surface reflection may provide clues to general fracture directions and

anisotropy but to accurately locate and characterize such features is a difficult task and requires high resolution subsurface methods. Using standard processing techniques, fracture zones were located which could be detected, but not located, by other means. This was accomplished by utilizing high frequency energy in a combination of crosswell and single well approaches.

3. From a rock physics point of view, we have shown that replacement of water with a gas (in this case air) produces large changes in the P-wave signal, even in such small features as a fracture with a width on the order of a millimeter. This is significant because although our wave lengths were on the order of one half to one meter, we still "saw" the fracture. This lends field evidence support for the displacement discontinuity theories that predict such effects, (Schoenberg, 1980, Pyrak-Nolte et. al, 1990a, 1990b).

Future work will pursue field and laboratory scale experiments to explain why and how such small features cause such large seismic anomalies, using S-waves as well as P-waves. Just as importantly, we will also take the high frequency crosshole and single well methods to larger scales with surveys in production environments. We feel that only in this joint basic/applied approach can we make true progress in developing useful methods for characterizing heterogeneous reservoirs.

Acknowledgments

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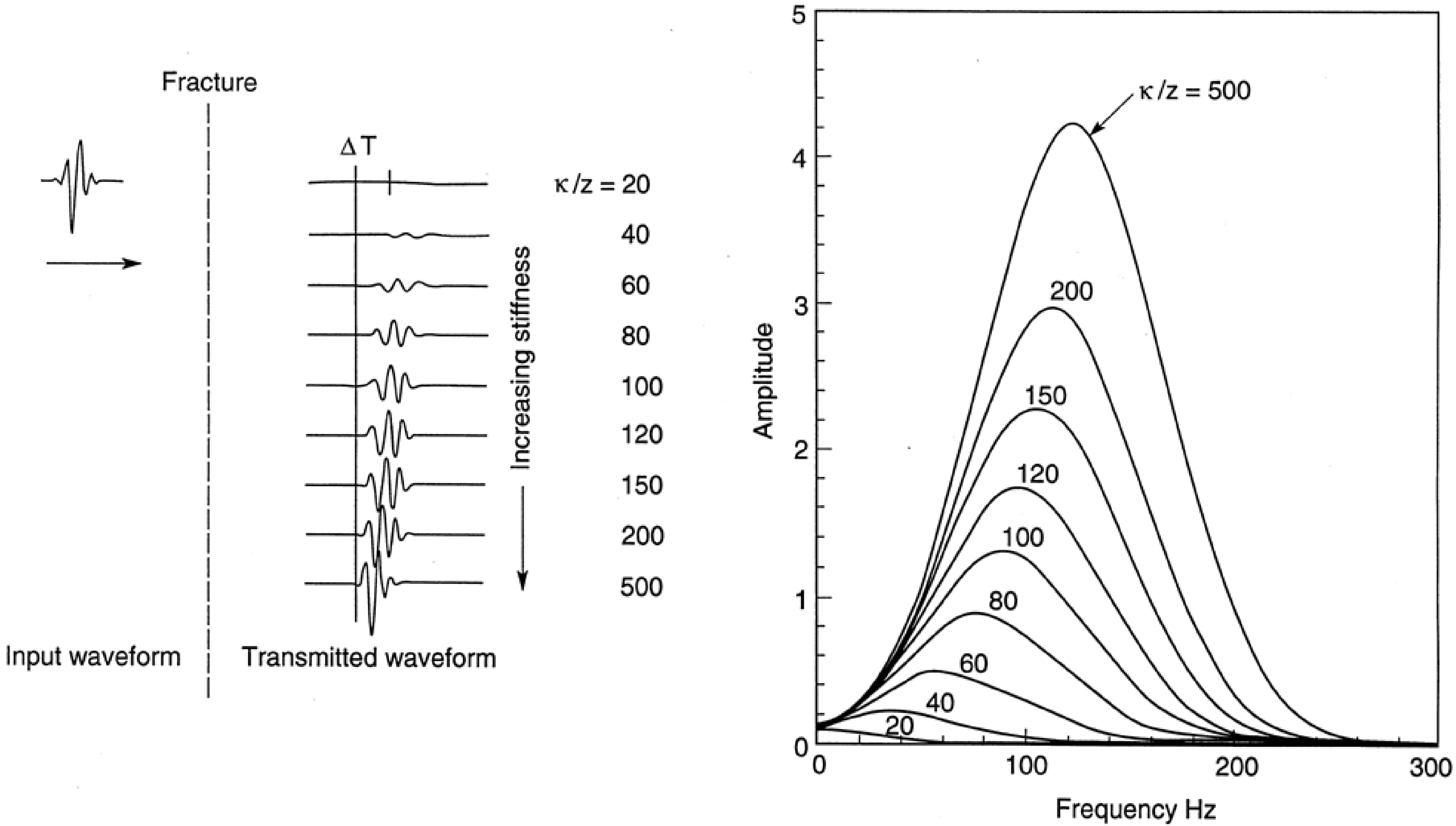


Figure 1. As fracture stiffness (k) decreases, frequency dependent decreases in amplitude and velocity are predicted.

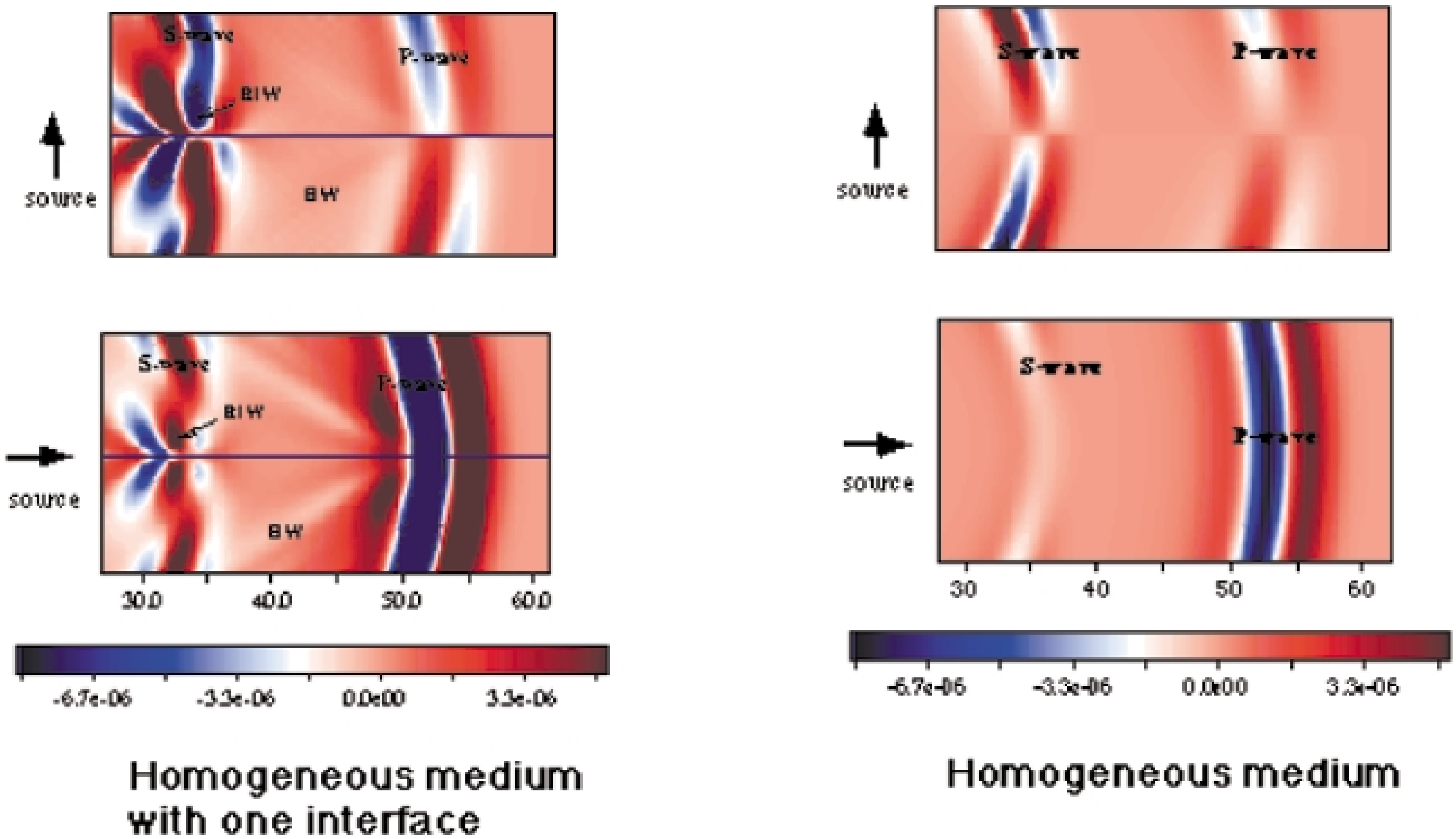


Figure 2. Numerical simulation showing a snapshot of the wavefields generated by vertical and horizontal point sources.

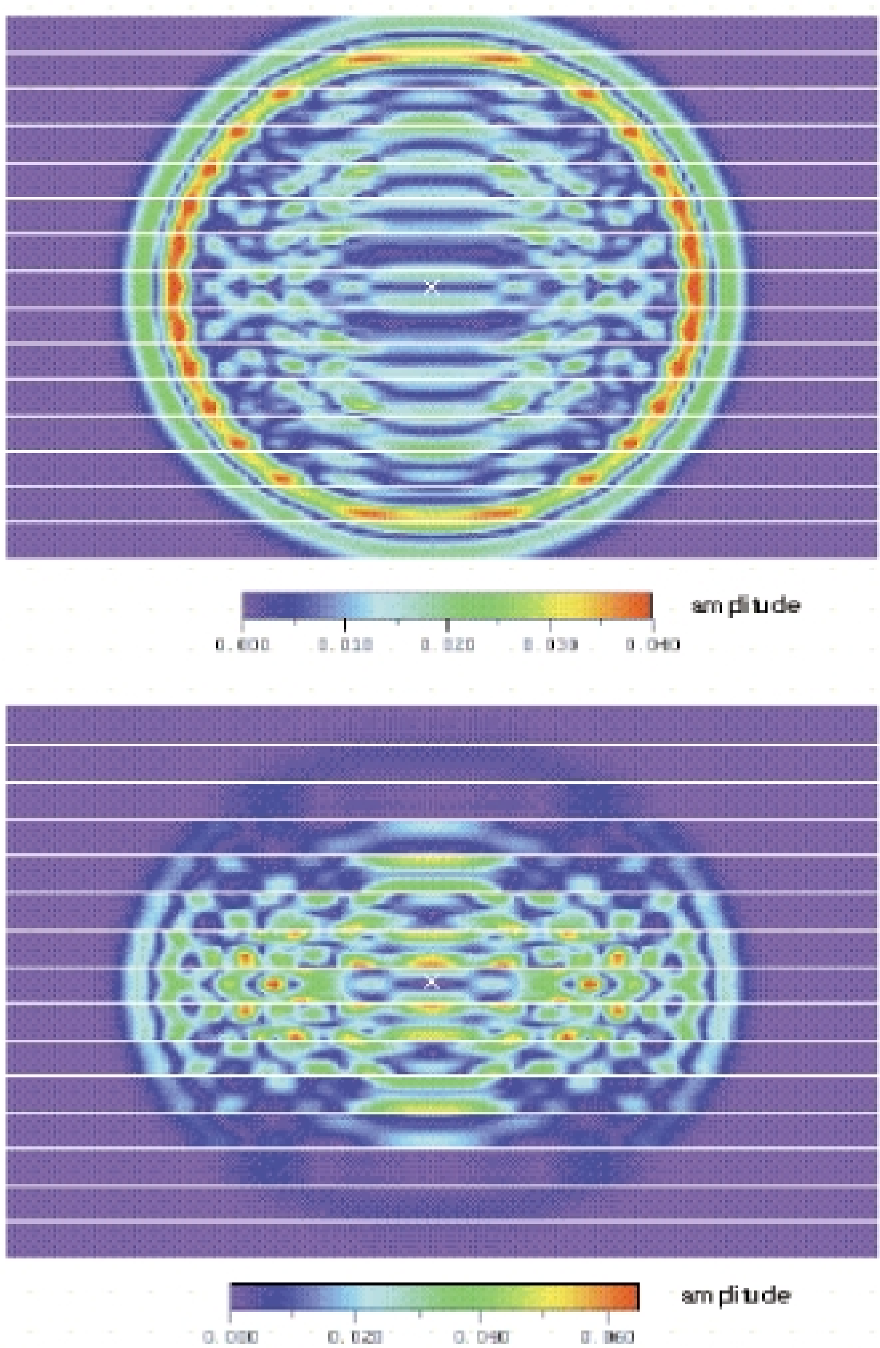


Figure 3. A snapshot of the wavefield for an explosion source in a medium containing equally spaced fractures of infinite extent for high fracture stiffness (top) and low fracture stiffness (bottom).

P-wave Reflection off a Vertically Fractured Layer

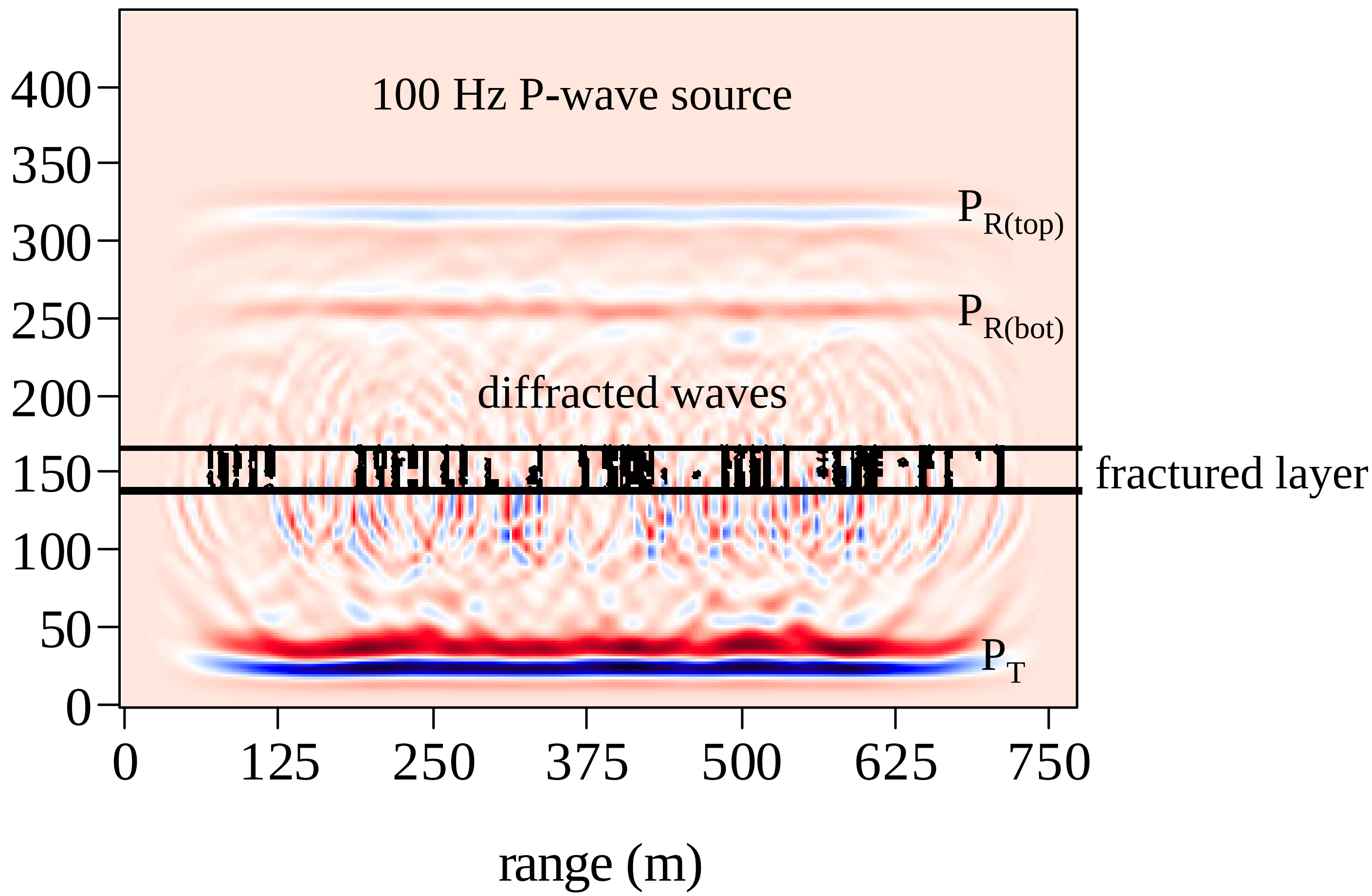


Figure 4. A snapshot of the wavefield for a case of a plane wave incident on a single layer containing fractures of finite length and irregular spacing. Reflected and transmitted waves, as well as diffracted waves, are observed.

Before and After Crosswell Air Injection Imaging

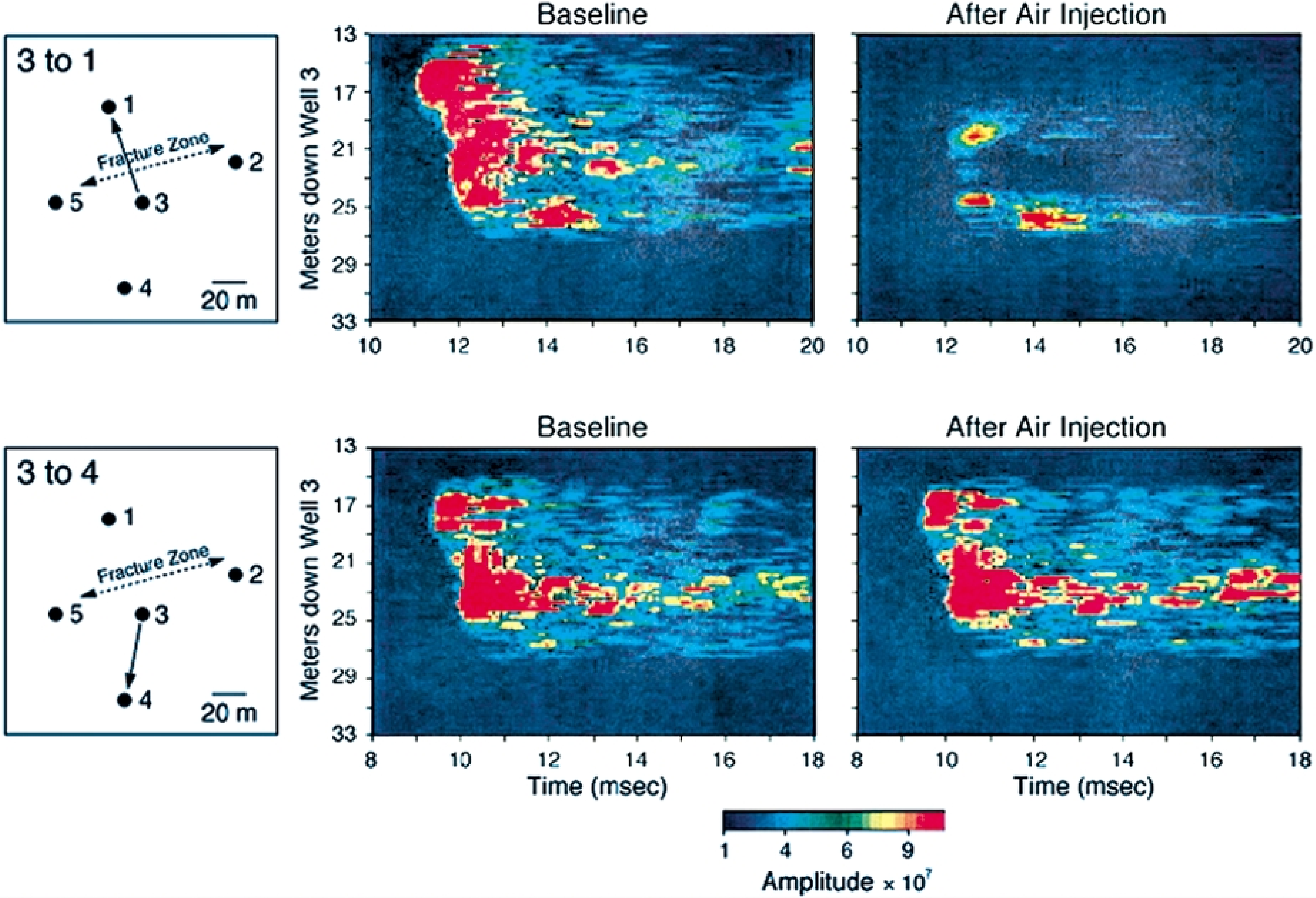


Figure 5. Crosswell spectral amplitudes as a function of depth and travel time before and after air injection in well 5. The energy transmitted between wells 3 and 1 (top row) shows clear change in amplitudes while the energy transmitted between wells 3 and 4 does not change amplitude. The fracture zone connecting wells 5 and 2 was also identified by hydrologic inversion and by singlewell reflection imaging.

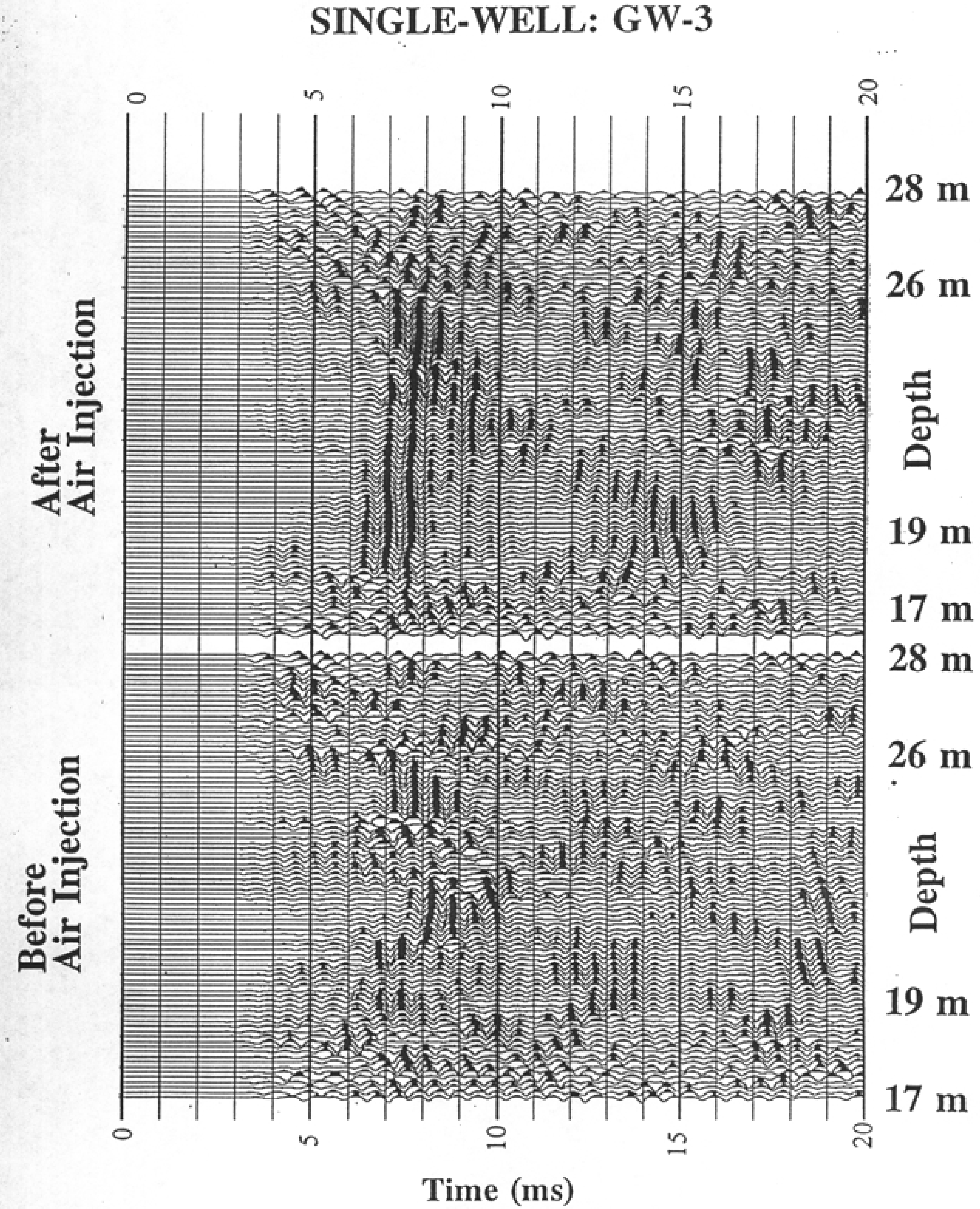


Figure 6. Crosswell monitoring during air injection. The source in well 5 generated a trapped fracture interface wave (generalized Rayleigh wave) which traveled along the fracture. The change in amplitude can be related to the change in fracture stiffness as air displaces water in the fracture.

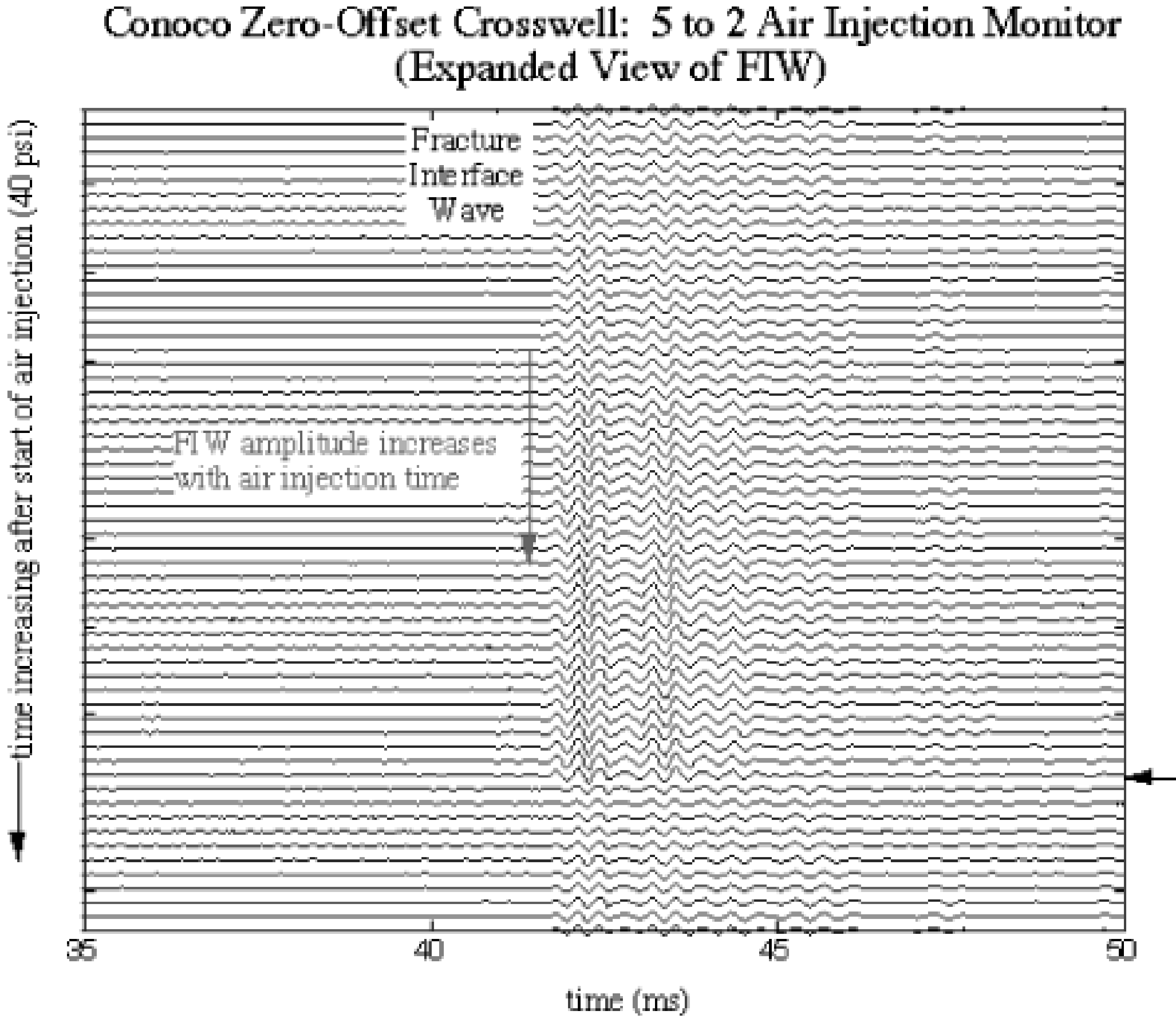
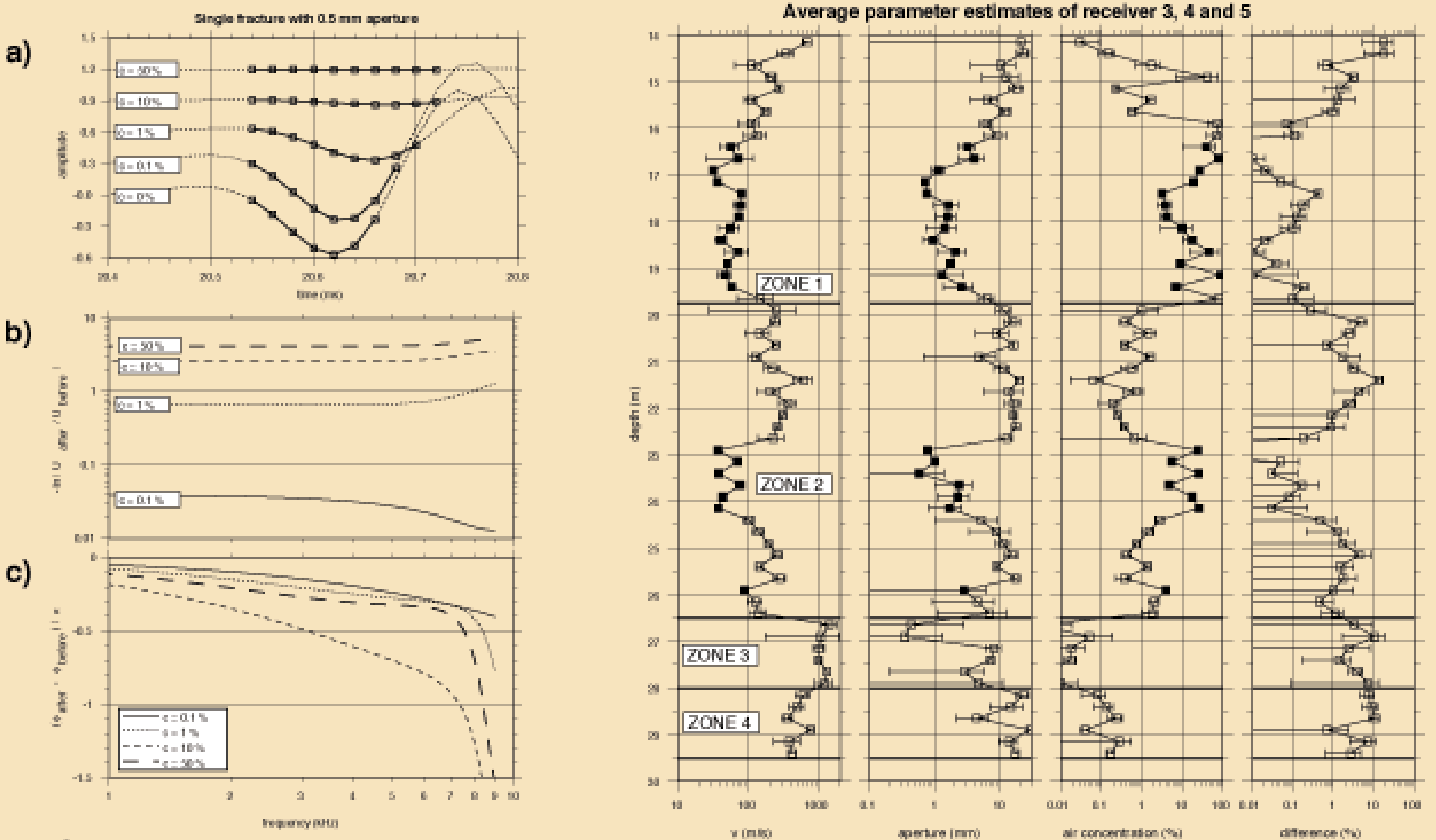


Figure 7. Crosswell monitoring during air injection. The source in well 5 generated a trapped fracture interface wave (generated Rayleigh wave) which traveled along the fracture. The change in amplitude can be related to the change in fracture stiffness as air displaces water in the fracture.

Modeling and inversion of crosswell seismic data for properties of the fracture zone between wells 2 and 5.



a) Seismograms, b) moduli and c) phase changes for different air concentrations.

Estimates of fracture aperture and air concentration. Reliable aperture estimates are only obtained if the velocity is below 100 m/s.

Figure 8